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TEAM PROBLEM SOLVING:
EFFECTS OF COMMUNICATION AND FUNCTION OVERLAP (U)

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HARRY G. ARMSTRONG AEROSPACE MEDICAL RESEARCH LABORATORY

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Armstrong Aerospace Medical Research Laboratory

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A theoretical framework is developed to assess factors that affect crew productivity in problem solving tasks. A taxonomic analysis is expanded to consider interrelations between categories of factors, namely characteristics of resources, of the task, and of the group. Experimental results are presented to examine the effect of degree of communication and of function overlap on problem solving by two-person crews. The data suggest that communication facilitates problem solving when there is no function overlap; when communication is restricted, problem solving is impeded when there is partial overlap of function. The findings are discussed with a focus on the concept that crew behavior is not a simple aggregation of the contributions made by individual crew members. Keywords:

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SUMMARY

This report develops a theoretical framework of factors that affect crew productivity, specifically as it relates to team problem solving. It extends taxonomic efforts to include consideration of interdependencies between these factors. It then offers an analysis of experimental data that serve to examine the effect of opportunity for communication and of the degree of function overlap on problem solving by dyads (two-person crews). The data indicate that although communication has a benficial overall effect on problem solving, this effect is moderated by the degree of function overlap that is in existence. Problem solving is facilitated by communication when there is no overlap of function; when communication is restricted, problem solving is uniquely impeded when there is partial overlap of function. These findings are discussed in the context of the observation that dyad behavior is not a simple aggregation of the contributions made by individual dyad members.

PREFACE

The research underlying this report was conducted while the author was a member of the Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, during a sabbatical leave from Wittenberg University. The support of Charles Bates, Walter Summers, and Kevin Holloran is gratefully acknowledged. The informed and substantial contributions of Sharon L. Ward and of R. J. Poturalski were essential to the success of this research. Special mention is made of the creative, skilled, and meticulous efforts of Danny Bridges, who wrote the computer software for the experimental task.

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THEORETICAL FEATURES OF THE C^3-TASK

In command, control, and communications (C^3) systems, crew members usually have to solve problems jointly. Team tasks may vary from each other, but usually they include some task components which can be identified and which thereby permit a degree of generalization across C^3-systems. In accord with an information processing approach, an input stage and an output stage can be identified, the two stages bracketing the actual work of the crew. Input and output have to obey pre-determined format requirements; therefore the productive component of the crew's intervening activity is restricted to behaviors compatible with these requirements. Within the limits established by the boundary requirements, the crew has to follow sets of rules in its intervening work, rules that are prescribed and that are expected to be valid in a constant and predictable manner for all possible inputs the crew might receive (even though the rules may be flexible and permit or even encourage individual or team discretion).

THE C^3-TASK AS INTERVENING ACTIVITY

To identify the characteristics of the crew's intervening activity amounts to developing a taxonomy. Scientists are typically circumspect when developing a taxonomy, for good reason. It is all too easy to overlook categories that others consider important, thereby invalidating much of the effort. Further, a feature most desirable in any taxonomy is its internal and external consistency and the resulting face validity of the system, which mandates that the taxonomy be compatible with approaches that have gained seniority status in the field, by virtue of their demonstrated usefulness.

Requirements such as these encourage great caution and may result in a lack of originality. The problem is particularly vexing if one attempts to avoid commitment to a theoretical heritage. Unfortunately such an uncommitted stand has little to offer that would be novel territory to those working in the field.

With this approach to modeling in mind, it is suggested that the crew's intervening activity can be interpreted, for most C^3-situations, as a matter of dealing with problem solving tasks. The crew's problem is to diagnose the state of a subset of the environment by the process of matching relevant information from the environment to a set of templates. This model is sufficiently open that it can be applied to various complex information processing tasks. It is easily applied in the contexts of detection and recognition tasks, but its appeal grows as one uses this approach to viewing the nature of a multidimensional decision making task or an open-ended problem solving task. The complexity of these tasks is often poorly understood if one merely considers them as complex or ambiguous stimulus patterns. That characteristic may well be present in the task, but the difficulty may also be located in an entirely different realm: The available templates may be overlapping, they may each contain incomplete and sketchy information, or the set of templates may not be exhaustive of all possibilities. The situation in which templates (or, more generally, rules) are expected to be fail-safe and free of error, and in which they simply do not apply or may even be misapplied, has been richly satirized, most notably in Heller's (1955) Catch-22. The same situation, however, is also quite familiar to anyone who has ever worked in a C^3-environment, as well as to persons who have prepared checklists, operating manuals, computer programs, and procedural handbooks.

THE CREW PRODUCTIVITY CALCULUS

Whatever the crew's task is, the crew can do it well or poorly, and typically its performance is assessed in terms of some index of productivity. Persons or organizations in a position to judge crew productivity commonly are quite reticent in rendering a verdict about crew performance, possibly because they recognize the complexity associated with any calculation of productivity. Obviously it is insufficient to think of crew productivity strictly as an output variable, for productivity is a relativistic concept, affected by a large number of variables. In addition, these variables are interactive with each other in a non-trivial manner; they mutually moderate their individual effects.

To attempt an understanding of the manner in which variables enter into the calculus of productivity, it is necessary to establish a list of such variables, to define the variables in some operationally useful fashion, and to speculate on the manner in which the variables may interact. This is the point at which a taxonomic effort of major proportions would seem indicated. The present paper is not the place to render an exhaustive taxonomy, particularly since a variety of more voluminous documents of the sort are available, but it may be the place to present, in limited scope, a programmatic attempt that may be desirable in any taxonomy, namely to integrate the list of variables with each other in such a way as to make explicit some of the postulated interactions between them.

VARIABLES ENTERING THE CALCULUS

Four major categories of variables affecting crew productivity can be identified, and these categories can be broken down further in the manner used in the following discussion. No claim is made that the list might be exhaustive. Further, there is no compelling reason why another breakdown might not be used in place of this one, except that the present categorization is thought to be particularly consistent with information-theoretic and experimentally focused approaches in the field. The following categorization is proposed:

- Resource characteristics
  - Resource availability
  - Resource variability
- Task characteristics
  - Task structure
  - Task load
  - Compatibility of resources with sub-tasks
- Group characteristics
  - Group size
  - Group structure
  - Leadership
  - Communication among crew members
  - Function allocation
- External constraints upon crew

Resource Characteristics

Resources can be thought of as "all the relevant knowledge, abilities, skills, or tools possessed by the individual(s) who (are) attempting to perform a task"

(Steiner, 1966, p. 274). In modern C^3-systems it is no longer justifiable to think of resources exclusively as human potential, supported by hardware. There is hardly a crew of this sort at work that does not have access to decision aids and various means of processing information. For this reason the relatively impersonal term is preferred over others that would be more restrictive. Resources can vary in two major dimensions that are thought to affect productivity, namely in availability and variability.

Resource Availability. Resource availability may be considered central to crew productivity, for resources are the agents that act upon a task, and without such action it is not meaningful to speak of productivity. Resource availability is in itself a multi-dimensional concept. The contributions of the sub-variables are likely to be interactive with each other, or at least non-independent of each other. For the purposes of this analysis it is thought best not to include crew size as one of these dimensions, although one could certainly insist on doing so. There are, however, enough others. The level of individual training and of group training are two major dimensions, and these, of course, typically receive great emphasis in the establishment of C^3-crews. An additional major set of dimensions is associated with the various abilities and aptitudes crew members bring to the situation, often recorded as a bewildering array of test scores with frightfully low validity for the specific purposes to which they are put. Resource availability becomes more complex yet when one considers situational dimensions such as fatigue, boredom, anxiety, or competitiveness. All these dimensions, in a complexly intertwined manner, make up availability of resources. The effect of this complex composite, of course, in turn is still modulated by virtually all other variables associated with either the task or the group. The taxonomic challenge is humbling.

In practical application the prerequisite of resources for productive performance of a group has on occasion led to the operationalization of the concept of "resource" as group size: If a team cannot handle the given task, the solution is to increase the team size. This translation has merit but is also limited in usefulness. Size, as will be shown, has its own characteristics affecting productivity, but beyond that its relation to the availability of resources is only approximate. In particular, group size is normally directly related to total resource availability, but usually only in the sense of redundant resources, not necessarily in terms of different, unique resources (Shiflett, 1979). In addition to the availability of resources, then, their variability has a notable effect upon productivity. Even at this point it is worth noting that availability and variability cannot be viewed as orthogonal to each other.

Resource Variability. Resource variability, briefly alluded to before, is closely related to resource availability. While the availability of resources can be thought of as undirected potential that is at hand, variability responds to specific needs that must be addressed in a directed fashion. As a result, variability of resources is much more sensitive to specific task demands. The concept of resource variability, specifically as stated in the form of the distinction between redundant and unique resources (Shiflett, 1979), is important to an understanding of the forces affecting a team in the process of working on a task, as well as the likely productivity of the group. At the very least, this concept helps to focus to some degree on the formidable complexity of the relationship between the available resources and productivity. Nor is variability always desirable. For a sculling crew it is most important that individual expression and personal initiative be kept at a minimum. The winning crew likely consists of people who contribute nearly identical resources. A single crew member can virtually assure losing a race, by the simple expedient of contributing something unique. This would be an example of conjunctive task constraints (Shiflett, 1979), the case in which the strength of a team is limited by its weakest member. By contrast, disjunctive constraints apply when the productivity of a team is determined completely by the best member's performance. Here it is most likely that a high degree of resource variability is desirable. In most cases the contributions of all team members count, though commonly in some weighted manner. On a sailing vessel, for example, each crew member is expected to contribute specific skills and actions in a pattern integrated with that of other crew members. Here, too, each crew member can practically clinch the loss of a race, but in this case by the failure to contribute something unique. Given a particular task, then, it is not only important whether the requisite resources are available but how they are distributed among group members.

Task Characteristics

In the analysis of resource characteristics, task dimensions emerge as a set of major moderator variables affecting the effect of resources on productivity. Task variables are not infrequently considered strictly as input dimensions, but the approach taken here suggests that the nature of the task can affect in substantial ways the manner and effectiveness in which resources are applied toward an outcome. Expressed another way, it may be reasonable to think of the composite effect of task and resource variables as more than a statistical interaction, namely as the effect of task variables on resource variables as they, in turn, affect productivity. An analysis of moderating effects of task variables was also offered by Shiflett (1979), based on previous work by Slovic and Lichtenstein (1971). Shiflett made the suggestion that, contrary to common practice, redundancy (and more generally all aspects of resource variability) should be considered a characteristic of available resources, not of environmental or, as they are frequently classified, input dimensions. He proceeded to show that redundancy can be manipulated by making it a function of the task (by means of arbitrarily dividing the task in several ways). With this evidence as backbone, his argument also logically supports yet a more basic construct, namely that task variables moderate the effect of resource variables (although this argument was neither stated as his purpose nor developed in his paper).

Task Structure. For the sake of consistency with the information-theoretic approach adopted here, a relatively undifferentiated breakdown of possible task structures is suggested. This approach is two-dimensional, the dimensions referring to the manner in which input and output flow occur and to the nature of the decision rule imposed on the crew.

The first dimension, that of input and output flow, is also commonly known as the distinction between static and dynamic tasks. In static tasks, input is given as a complete entity, and there is, after processing, a single output. In dynamic tasks, input occurs in installments over a period of time, later inputs sometimes overriding earlier ones. Similarly, outputs under such circumstances are commonly made in series of provisional responses that are revised as new inputs are integrated with previous ones.

Experimenters have a tough time handling dynamic situations since it is almost impossible to specify the magnitude of independent variables at any time. Consequently, they prefer the study of static situations. Actually there is a very good theoretical rationale available for doing just that: Even a dynamic task environment can be considered as one that is momentarily static between successive inputs, and the rate of inputs and of required outputs can be viewed as a separate independent variable, namely the time allowed for solution of discrete problems. Dynamic tasks can therefore be considered static tasks in which processing time is not the usual dependent variable but an independent one. The researcher's challenge is to control this variable, and a legitimate way to do so is to make inputs discrete.

As always, the problem is more involved than it appears at first sight, for there is another important distinction to be made between static and dynamic tasks. Dynamic tasks formally require memory for previous inputs on the part of the crew, for the crew's task is to respond to the aggregate of present and previous inputs. Static tasks, on the surface at least, have no such requirement, since each successive task is an independent input. Even this distinction becomes blurred in real-life situations, however, since memory for decision rules has to be active in both task types and since this memory includes representations of previous solutions, both in static and dynamic tasks. As it turns out, then, the memory requirement is present for both task types, formally for dynamic ones and informally for static ones. Memory has major effects on productivity in either task type.

In the actual experience of C^3-crews, the distinction between static and dynamic tasks is likely to be secondary to the subjective assessment of crew task load. Whenever any subsystem is taxed to the limit, the effect is most readily experienced as an increase in "pressure", or in subjective task load. Due to the fact that processing time is not under the control of the crew in a dynamic task, it becomes scarce and valuable, and its shortness is experienced as task load. Task load, discussed in the next section, is not independent of task structure.

Task structure, defined in terms of required decision rules, is a well-documented area (i. e. Fisher, Edwards, and Kelly, 1978, Galanter, 1962, Dember and Warm, 1979, Lindsay and Norman, 1972). The field, more than most others, is open to an information-processing analysis. At the same time, it is consistent with some of the approaches to understanding the structure of human intellect, most notably Guilford's (1967) work. The tasks, often in alternate terminology, can be categorized as ones requiring detection, recognition, discrimination (Galanter, 1962), classification, feature analysis, feature synthesis (Lindsay and Norman, 1972), and attributive judgment (Dember and Warm, 1979). The general view is that this series increases in terms of difficulty or underlying operations, detection being the simplest process and attributive judgment the most complex one. It should be noted that these categories do not increase systematically in terms of input complexity, but merely in terms of the complexity of the decision rules. Thus detection requires a single binary rule, recognition requires several such rules, and attributive judgment requires a complex array of rules, some of which are conditional on other rules, often in a probabilistic manner.

Decision rules substantially determine the structure of what it is that a crew does before delivering an output. Clearly the matter of the relevant decision rule interacts with most of the other dimensions of productivity, simply because they all are moderated by the rule that is to be used.

Task Load. Perhaps because it is most readily quantified, task load is frequently at the forefront of variables identified as task dimensions. Task load, one might hope, is a relatively pure independent variable which does react with other variables. Unfortunately such hopes are not warranted. Task load does indeed interact with other variables. One is familiar with the phenomenon that "things were so hectic that the boss was helping out". In other words, under conditions of high task load, administrative and supervisory functions are likely to be pushed into the background (Hill, 1982). Conversely seen, conditions of low task load permit a corresponding increase in activities devoted to administration and supervision. The interaction of task load with features of group structure as demonstrated in this illustration is no isolated case. Task load also interacts with other variables. As was shown previously, its effect is moderated both by available resources and by their variability. If one considers use of the term "capability" rather than "resource", its relationship with task load gains clarity, for a task load may be overwhelming to a group of limited capability, yet challenging or even gratifying to a more capable group.

The number of variables contributing to task load is open-ended and very much a matter of individual preference. Due to the general interest in task load, several excellent taxonomies may be found in human engineering handbooks. Many of the variables, such as task difficulty, task variability, required response skills, speed and accuracy requirements, differential consequences of success and failure, backlog of tasks, and output demands, are reflected in most breakdowns in some form or other. The chief problem presented by these categories is one of operationalization. Several of these categories can be operationalized with relative ease into dependent measures. Task difficulty, for instance, is easily translated into some measure such as response latency or error rate. Unfortunately, the theoretical requirement imposed on these categories is that they act as independent variables, variables whose magnitude is not measured by the responses they produce, but whose magnitude is manipulated so as to produce different responses in the first place. The scientific task quickly becomes muddled and unsavory: The researcher has to measure the effects of these variables under a variety of conditions, then use these conditional effects to assign estimates of the magnitude of a variable as it is applied to a new situation. These transsituational definitions (Meehl, 1950) are problematic and clumsy. At the same time, they are often all that is available.

Compatibility of Resources with Sub-Tasks. When a plumber arrives on a service call and finds that the refrigerator needs repair, it is likely that he does not have the necessary tools even if he should have the required skills. Unproductive mismatches of this sort are part of the regular experience of C^3-crews, though typically in less spectacular form. Quite often most component sub-tasks are within easy reach of solution, except for one or a few sub-tasks that elude the available resources. The absence of a single essential tool can result in a scramble for alternate solutions that would never be considered if other important resources were also missing. This behavior is consistent with predictions of social motivational theories such as cognitive dissonance theory (Festinger, 1957). The closeness of the solution and the previous investment of effort in the solution of other sub-tasks make it difficult to drop the task even if it becomes obvious that the total task cannot be mastered. This situation arises with particular frequency when the underlying decision rules are complex, when the group structure makes proper resource allocation difficult, and when the resources have insufficient variability. This situation obviously also makes for exceedingly low group productivity.

Group Characteristics

The need to distinguish resource characteristics from group characteristics was pointed out previously. While resources need to be identified in relative abstraction from the persons who may contribute most of these resources, it is also necessary to identify those group characteristics that go beyond a discussion of resources. Subsumed under the heading of these group characteristics are size, structure, leadership, communication mechanisms, and selective function allocation within the group. Beneath these explicit topics, and embedded within them, is the complexly vibrant organism of the group, whose behavior is much more poorly understood even than that of the individual. Obviously, the suggested categories of group characteristics constitute an example of serious reductionism.

Acknowledging the need for unavoidable simplification, the break-down used here seeks to be responsive to attempts to understand any pre-established form in which a group may operate, whether that form is imposed by external rule, by habit, by adaptation to task demands, or by characteristics of the individual members of the group.

Group Size. Group size has an obvious effect on productivity, though not a simple one. Folklore suggests that four eyes see more than two, and two heads are better than one. This notion is also known as the "pig principle": If something is good, more of it is better. Upon some reflection, however, an analysis of the situation shows that things are not quite as simple as the pig principle suggests. If it takes a bricklayer eight hours to lay 400 bricks, two bricklayers may well perform the same task in four hours, but there is a limit: Eight bricklayers will not finish the task in one hour, as a naive application of arithmetic rules might indicate, but they will be most vexingly in each other's way. There may well be a point of diminishing returns at which an increase in group size reduces group productivity. Such a relationship might be the reason why assemblies appoint committees; it would take the full assembly a longer period to resolve a problem than it would take a small committee. There is ample empirical evidence to support this hypothetical concept: Groups almost always perform at a level inferior to the statistical expectation derived from the performance of the individual group members (Hill, 1982).

There are several possible reasons why increasing group size may reduce productivity per person or even per group. Among them is the concept of "process loss" (Steiner, 1972), which may be thought to result from unproductive events, such as the voicing of a faulty hypothesis by a group member (and a reply by another member proving it faulty) after a correct hypothesis has already been applied. The tendency of less productive group members to demand and obtain "equal time" can be similarly wasteful, as can the phenomenon of "social loafing" (Latane, Williams, and Harkins, 1979).

Group Structure. Group size interacts with other primary variables which are thought to affect group productivity. Group size typically is related to group structure, since larger groups are more likely than smaller groups to be organized in a hierarchical or similar form. Productivity is directly affected by such structural features, primarily because resources need to be allocated to maintenance of group structure, not just to the task at hand. Commonly, the larger a group is, the greater is the proportion of resources that is likely to be reserved for organizational purposes. Similarly, the more structured a group is for any reason beyond size, the more resources are consumed in the process of structural maintenance. This observation does not suggest that structure is undesirable for groups of any size. The alternative of an unstructured, large group is likely to be chaotic and quite unproductive. It may be best to think of group structure as a mixed blessing: It facilitates group processes which could not take place without it, but it does so at an expense: Resources have to be reserved for its operation.

In a competitive environment such as the business world, where relative productivity, or efficiency, is a matter of survival, successful organizations are highly sensitive to this problem, and their goal is to find for themselves a structure that has maximal organizational advantages while requiring a minimum of resources for its functioning. Even here the problem becomes strangely complex. The executive must search for means of eliminating executive overhead, but only within limits, since the executive's own position must not be threatened. The best way to assure the security of this position is to surround it by less essential positions, thus producing wasteful hierarchy. In other words, even when it is essential that group structure consume a minimum of resources, groups show a tendency to inflate the allocation of resources to structural purposes.

To counteract the tendency for proliferation of structural features in the functioning of a crew, various safeguards are available, particularly when the structure of the crew is not a matter of the group's decision. Most C^3-crews are clearly embedded in an externally imposed structure, and little room is afforded to individual discretion regarding the operation of the team. Nonetheless, crew effectiveness varies since many administrative functions are exercised at the will of persons in charge, or as a function of emerging personal relations of friendship, alienation, or convenience within the crew.

The nature of group structure affects crew productivity in a manner that goes beyond degree of organization. Group structure implements access to task-relevant resources. This facilitating effect is an absolute necessity when tasks have disjunctive constraints (Shiflett, 1979), for without it the assignment of appropriate crew resources would be a matter of chance, usually with microscopic success probability. If the task mandates communication between crew members, as is frequently the case, then the effect of group structure may be limiting, particularly if the structure is of a strictly hierarchical nature, forbidding lateral communication.

Leadership. When one encounters a group engaged in some organized activity, be it a parade or a picnic, one is convinced that one may legitimately ask: "Who is in charge?" A group that claims any purpose at all is expected to have some structure, and for all practical effects structure implies leadership. In fact, a group without some identifiable leadership is more likely identified as a crowd or, if engaged in undesirable behavior, a mob, and one would never expect productive behavior form either one. Leadership may be identified as an integral part of group structure. In essence, leadership formalizes structure. It signifies more, though. It stabilizes role differentiation in the group, and it establishes channels of communication. It designates responsibilities and privileges, and it lends credibility to persons in leadership roles even though they may not engage directly in those activities that constitute the purpose of the group in the first place. Leadership also serves to make possible an orderly means of communication between the group and other social entities. Further, it permits someone to engage in planning, budgeting, review, and other processes that would not be compatible with carrying out the immediate productive functions of the group. Finally, leadership has a yet more elusive function, namely to provide a motivational means of maintaining a high productivity level among group members over sustained periods of time.

When one considers the many attributes associated with effective leadership, it is not surprising that leaders are a valuable commodity, and one that is found less often than it is offered. It also is not surprising that defective leadership is a rather prevalent problem in large numbers of C^3-environments. Effective leadership requires a composite of skills that is unlikely to occur in any individual. The common manner in which persons end up commanding positions of leadership is widely linked to a seniority system, which does not assure the development of leadership skills in the least.

Since leadership has such sweeping implications for the structure, functioning, and well-being of the group and for its long-term vitality, it is not surprising that its effect on group productivity has major proportions. The same can be said for many other variables, of course, and those effects should not be considered less important. Nonetheless, the effects of leadership are especially capricious because it appears so difficult to predict, control, or manipulate any of them. In fact, it may well be impossible to identify in an unqualified manner what might constitute a good leader simply because of the interactive effect of leadership and other variables. What may be excellent leadership for one type of task or for one group size may be terrible leadership for another.

Communication Among Crew Members. On the surface at least, communication among crew members would appear to be an essential requirement for the proper functioning of a team. Communication is so much part of the popular definition of what makes up a team that one feels resistance to the very thought that anything might fare well without it. In fact, communication is frequently associated with a general state of interpersonal well-being, and for this reason alone a team would be suspect if its members did not engage in communication. Communication is an important component of social grace, of openmindedness, and of a life style characterized by mutual interdependence. Communication is so central to our concerns that the right to exercise it is guaranteed by the first amendment of the Bill of Rights. The thought, then, that a restriction of communication might be advantageous under any circumstances is rather foreign to our sentiments.

Even in rational terms it would seem that restrictions of communication would necessarily interfere with the chief business of any C^3-crew, namely to solve some problem that can only be solved by the crew as it communicates and thus collates the individual contributions. After all, a group of individuals who do not communicate with each other cannot be expected to be anything more than the sum of its parts, and only through communication can the group become more than the sum of its parts. It would be difficult to argue with this view on rational grounds. On empirical grounds, though, the matter becomes more cumbersome. For there is ample evidence that a communicating group almost invariably produces less than the sum of its parts. In several studies (Faust, 1959, Fisher, Edwards and Kelly, 1978, Gustavson Shukla, Delbecq and Walster, 1973, Howell, Gettys, Martin, Nawrocki and Johnston, 1970, Morrissette, Crannell and Switzer, 1964) it has been shown that group performance is only marginally superior to the performance of an individual and markedly inferior to any plausible statistical aggregate of the individual potentials. Hill (1982) proposed that whatever superiority a group has over an individual is not so much a matter of group processes as it is determined by the most competent member of the group. "For easy tasks, performance was often determined by one competent member. The group's size increased its probability of containing at least one member who could solve the problem. For multiple-stage problems, groups had a greater probability than did individuals that at least one member would be able to solve each stage" (Hill, 1982, p. 525).

How can these results be understood? Clearly they run counter to expectations, as well as to common practice based on these expectations, and they demand an interpretation with some appeal and with characteristics that would make it testable. To date, such a powerful theoretical formulation has not been advanced yet, though several more provisional thoughts on the matter have been offered for discussion and research. Among them, one that has survived a variety of tests is Steiner's (1972) concept of process loss, alluded to previously. This difference between the theoretical maximum performance of the group and its actual performance was described as resulting from unproductive events. As seen in the light of our current discussion, unproductive events of the kind mentioned all are communicative in nature. In such tasks communication is likely to be distracting, it invites group members to let the other person take charge, results in an unproductive competition, or may stifle individual originality. In other words, communication, the activity which is central among characteristics considered desirable in a group, is also the activity which results in low group productivity.

Another interpretation of low group productivity as a result of communication has been offered by Arrow (1963), who sees groups as confronting a perplexing problem, namely the social utility problem. It may be assumed generally that an individual has a transitive preference ordering of utilities assigned to various alternatives. Thus, if a person prefers alternative A over alternative B, and B over C, then that person is likely to prefer A over C. When several group members each have a transitive but non-identical preference ordering of a series of alternatives, however, a pooling of their preferences does not necessarily lead to a transitive ordering of preferences for the group. Precisely this set of circumstances is very common in group situations. It may be, for instance, that several courses of action are available to a governing body to replace a course that is currently being followed. It is quite possible that the vast majority of members would prefer one or another of the alternatives to replace the old procedure; however, their preferences of the choices are ordered in several different ways such that they balance each other, and the old course is continued by default. In fact, various sophisticated voting procedures have been developed to deal with this problem. These systems adequately deal with non-transitive preferences in an actual voting situation. Being relatively complex, they are not commonly employed in group situations in which an informal atmosphere is considered desirable. Also, they do not lend themselves well to application in a discussion situation.

Considering the disturbing paucity of positive effects of communication on productivity, one wonders why society attributes so many salutary qualities to it. One is left unsatisfied by these results, despite sensible efforts to interpret them. Why should popular thought on the matter be so far off course in relation to research results? A simple answer does not present itself. One possibility that might cover some ground is that communication may serve purposes other than those normally attributed to it. Communication may, in a way, serve more of a mental health function than is commonly thought. It may well be that communication is just as important for group productivity as are vacations and office parties. Without them the morale of the group would suffer, and team productivity would deteriorate. But while these activities are going on, productivity is near zero. An opportunity to talk to a group is likely to produce various rewards for the speaker, since the act of speaking to others provides opportunities for control and for verbal manipulation of a captive audience. Similarly, the opportunity to listen has its own rewards. The listener is being entertained, sits in judgment, and has time to prepare a comeback that will blow the previous speaker out of the water. People do this sort of thing free of charge at social gatherings all the time; why should they not be eager to do the same for pay while working in a C^3-crew?

Much as the effects of communication on productivity are in disagreement with popular expectations, they become even more unwieldy when one considers interactive effects of communication with other variables. It goes without saying that communication interacts substantially with virtually all variables associated with characteristics of resources, tasks, and groups. In this light, then, communication may not be the variable affecting productivity in the positive manner frequently thought, but it undoubtedly is a pivotal variable that affects productivity in major ways, for better or for worse.

Function allocation. Any group with even the least structure is characterized by role differentiation of its members. Persons in leadership positions are assumed to attend to administrative functions, and practically all positions have position titles and job specifications, formal procedures of allocating functions to group members. The need for role differentiation is not new to our society. Even sabre tooth society was based on a role differentiation which required that some group members would prepare food for eating while others had to assure that the group would be eating, not eaten. Nor is function allocation unique to human societies. Ants have taken the assignment of specific functions to group members farther than humans by quite a margin. In fact, various insect species can survive as species only by virtue of the fact that different roles are being fulfilled by different individuals. It may safely be said that function allocation is crucial to the effective functioning of any group engaged in a productive activity.

This observation shares some characteristics with the claim that food is good for you. Nobody disagrees, but the statement requires a more differentiated discussion. Questions of interest deal with effects associated with different types of function allocation and with ways in which the allocation of functions may interact with other variables.

The literature of available evidence is limited. In fact, despite the centrality of the topic little theoretical work has been done. One theoretical effort that has shown some results is the information-theoretic work of Boettcher and Levis (1981). Their work indicates that effectiveness of information processing by a group depends on organizational structure (i. e., function allocation) within the group as the structure interacts with task load (Levis and Boettcher, 1982). With increased task load, fewer "rational" strategies remain for the group. In other words, function allocation is meaningful as a device to streamline action when several options are available, but not when the work load restricts the number of options. This bottleneck effect is a familiar phenomenon in organizations in which job descriptions are so brittle as to prevent task transfer between persons with different job titles. Levis and Boettcher suggest that the type of function allocation, not merely its degree, has an effect on performance, but their research has not entered into the parametric stage at which it would be possible to state just what the effects of different forms of function allocation might be.

Game theory, particularly as it explores nonzero-sum, cooperative games, might be expected to contribute a framework to the matter of function allocation. It does not. Rapoport (1966) is quite explicit in his argument that game theory is not concerned with cases in which the goals of the players are in agreement: "The coordinated game is ... trivial. The interesting features of nonzero-sum games derive from situations in which the interests of the players partly coincide and partly conflict" (p. 95). Furthermore, game theory is prescriptive rather than descriptive. It is not a theory of interpersonal problem solving behavior. "'Rational players' ... should not have any 'psychology'. Or, to put it another way, if they have a 'psychology', it must be an extreme one: they must be perfectly rational or perfectly ruthless or (if possible) both. For if their psychologies are not extreme, then two such players might have some psychological property in different measures, which necessitates an examination of these measures. This is a psychologist's task, not a game theoretician's" (pp. 104-105).

For a systematic understanding of conditions affecting the productivity of C^3-crews, of course, coordinated games are anything but trivial. The nature of a problem-solving group in the widest sense is that its members make their contributions in some coordinated fashion. Despite the fact that very little has been documented about the ways in which organized resource contribution (i. e., function allocation) affects productivity, some provisional hypothetical formulations may be advanced. Extrapolating from the work of Levis and Boettcher (1982), it would appear that a high degree of function allocation is beneficial for productivity under conditions in which tasks follow a predictable sequence of known steps. With increasing uncertainty regarding sequence or selection of steps, the benefits of function allocation could be expected to fade, particularly when there are any restrictions to communication of team members, or when the structure of the group prohibits that team functions be rearranged. It would further appear that tasks requiring the contribution of unique resources (Shiflett, 1979) benefit from a high degree of function allocation as long as task load does not produce bottlenecks, whereas tasks demanding contribution of redundant resources would not benefit from function allocation. These latter tasks, however, may need other forms of coordination, possibly through liberal means of communication. A large number of further formulations may be advanced, but they seem too tenuous to introduce at this point, without some means of verifying them. They all, as well as the ones offered for critique above, refer to the interactive contribution of function allocation with other variables.

External Constraints Upon Crew

An analysis of variables affecting group productivity is incomplete unless it acknowledges the external conditions under which the C^3-crew has to operate. Most of these conditions are not under the influence of the crew itself, but yet they affect the well-being and productivity of the team. These variables include conditions of ambient noise, light, and temperature, as well as space allocation, supplies, and available staff. They also include any restrictions of input and output functions pertaining to the team, in particular channels of communication. (A busy telephone line can slow down information from a C^3-crew in insurmountable ways.) More detailed lists of relevant variables constitute an integral part of human engineering handbooks.

SECTION 2

STUDY PLAN

The variables affecting the productivity of a C^3-crew have been depicted as a multidimensional, interactive array. The complexity of this array has not been matched by research in the area, both in comprehensiveness of studies and in their actual number. Nobody can be blamed for this situation, for it is a rather overwhelming undertaking to systematize the field so as to determine what the prevailing research needs are, and then to proceed with the needed research. On a restricted scale, that is what the present study sets out to do. In view of the previous discussion of relevant variables it is clear that no single research effort has the potential of providing closure to the field. However, even efforts of limited scope can contribute to a field that is as complex as this one. What is crucial about such studies is that the interactive nature of the matrix of independent variables is reflected in their design. In other words, single-variable designs are no longer a promising research strategy, since most of the interesting action takes place as interaction. The following research had as its goal the analysis of two variables as they interact with each other, namely function allocation and communication.

FOCUS OF STUDY

Communication within a C^3-crew is thought to be crucial to the functioning of such a crew, particularly when the task at hand requires interaction between the crew members. Such a requirement can exist for two reasons. First, the task may be one in which the resources are associated with different crew members in such a way that they all have to contribute their share before the crew can accomplish its mission. This condition has been characterized as having conjunctive task constraints and therefore requiring different resources to be pooled. Here the need for communication is a task characteristic. Second, subfunctions contributing to the accomplishment of the task may be allocated to members of the crew in such a way that coordination of activities is a necessity for successful crew functioning. Usually such a division of labor is associated with one or several features of group structure. The need for communication in this case, in contrast to the one described above, is a characteristic of group structure. Thus communication may be required in an organic fashion by the task, or in an imposed fashion by the system that is in effect. In both cases, the relevance of communication may be assessed best by observing the effect of restrictions on communication. The possible effects on productivity cannot be assumed to be linearly related to communication level, since the effect of communication on productivity has been shown to be anything but a linear function.

In keeping with an information processing approach to the study of C^3-crew productivity, the design used here views the most relevant situation for study as a problem solving task. Thus the present study focuses on effects of degree of communication and of function allocation on team problem solving.

HYPOTHETICAL FORMULATIONS

In agreement with the analysis of hypothetical and empirical effects of communication and function allocation presented previously, it was expected that these variables interact in a manner that goes beyond the concept of a statistical interaction. Concretely, it was predicted that the effect of communication would be facilitative to problem solving when functions are allocated to team members in a non-overlapping manner but not when the functions of team members overlap or even coincide. On the other hand, it was expected that performance would suffer most seriously when communication is restricted under conditions of non-overlapping function allocation. Again, it was expected that restricted communication does not affect performance adversely when functions coincide. These expectations are specific to a problem solving task which has characteristics somewhat comparable to those of a puzzle. A task of this kind is expected to be disjunctive and to rely heavily on the contribution of the strongest team member. If this team member does not have the opportunity to execute the relevant function, because it is not assigned to that person, then the only way this individual can offer support is by means of communication. It follows that a restriction of communication should interfere with efficient problem solution. On the other hand, when such a task is assigned to a team without separation of function, communication cannot add any benefits to the situation. It can, however, disrupt the problem solving process, for reasons shown previously.

OPERATIONAL DEFINITIONS AND TRANSFORMATIONS

The independent and dependent variables of interest can be operationalized in a number of ways. What was sought for the present purposes was a task that would preserve a relatively high degree of experimental rigor without sacrificing the possibility that the task might have recognizable similarity to requirements encountered by C^3-crews. In other words, face validity was considered an important characteristic of the experimental procedure.

C^3-Crew Characteristics

In a C^3-system, the individual excellence of crew members undoubtedly is desirable, but it is not the concern of those who rely on the functioning of the system. To anyone outside the C^3-crew, the matter of concern is the productivity of the crew as a whole, rather than that of any individual. For the purposes of the present research the total C^3-crew was therefore designated as the organismic unit under study. The implication is rather important since generalizations from the study are valid only in reference to C^3-crews. The far more common approach considers the individual the basic unit of concern. Commonly such a view is appropriate. For present purposes, however, it was thought inadequate.

For the sake of efficiency and of experimental control, the smallest possible crew size was adopted as the one to study. This decision to study two-person teams (also referred to as dyads) was not made lightly since group size has substantial direct and indirect effects on productivity. The choice of dyads over other crew sizes was based on the following considerations: First, among various crew sizes in actual use, the dyad is the most common. From the viewpoint of practical research concerns, it is more difficult to control pre-experimental relationships among the subjects and communication between them for larger crew sizes. Also, no greater generalizability is associated with any other crew size. Of course, any other crew size would have been more costly to study. Finally, the task developed for this study was particularly suitable for the study of dyadic problem solving.

Independent Variables

As indicated above, communication and function allocation were the independent variables under consideration, and their interaction was expected to have substantial effects on productivity in performing a problem solving task. Since function allocation can be manipulated as an independent variable only if it is imposed externally, rather than by virtue of different resources offered by the crew members or otherwise, it was varied by this method. Three levels of function allocation were chosen to correspond to situations thought to be reasonably common in the experience of operational C^3-crews. Also, these levels span the full spectrum of what is likely to occur in real-life situations.

At the low end of the dimension of function allocation is a level without function restriction, a situation in which all crew members have the option to carry out any functions they choose. At this level, each crew member should technically be able to solve the problem alone. This condition may be considered a control condition as it falls at the zero-point of the dimension under study.

A second level of interest is one at which function overlap is limited in such a way that each crew member is still able to solve the problem at hand, though in a sub-optimal manner compared to what could be accomplished by team work under the same level of function allocation. This level of partial function overlap is typical of many situations in which crew members have a choice between doing a task themselves and asking another team member to do it. The tradeoff is between two options, neither one of which is ideal. On one hand is the use of limited, cumbersome resources one member may have readily available without any ado; on the other hand is the chance to use more efficient resources which another team member may have access to, but this option requires transfer of control, explanation, discussion of courses of action, and other features of communication.

A third level of function allocation is one that completely removes function overlap from the crew. Here each member of the crew has functions that no other crew member shares, and that are crucial to the crew mission. This level, like the first one, is relatively clear-cut. It does not leave room for any ambiguity; the crew can accomplish the task only if each crew member contributes the allocated functions. Only when team members perform their sub-tasks in synchrony with each other will the crew be productive.

These three values of the variable "function allocation" can be regarded as points on an ordinal scale of measurement, as they certainly represent a systematic increase in degree of function allocation. On the other hand, when they are viewed with regard to their potential impact on the crew, they take on the characteristics of points on a nominal scale; they represent qualitatively different treatments, not treatments that consist of the application of different degrees of some property. This nominal characteristic of function allocation becomes even more vivid when it is seen in context with the second independent variable, namely degree of communication.

Only two levels were chosen for the independent variable of communication, namely a level of full communication and one of restricted communication among crew members. Intermediate levels were not implemented due to the great difficulty of operationalizing these points and the even greater challenge associated with insisting that subjects cooperate in such an awkward challenge. At the level of full communication crew members experience no restriction in their choice of interaction. At the restricted communication level there is no possibility of direct, verbal interaction. This level, as will be seen, is by no means a zero point along the dimension of degree of communication. While crew members may not be able to talk with each other, they certainly are able to communicate to each other approval or disapproval of courses of action taken by a team member, or even to control actions of the other by restricting that person's choices, an option that is available even when there is no overlap of functions.

The two independent variables identified for this study form a 3x2 factorial experiment. Even so, the previous discussion of the complex interdependence among variables suggests that each one of the six resulting treatment cells presents quite a unique set of circumstances with effects that may be harmful or beneficial to crew productivity. There might also be cases in which some positive effects offset other negative ones. It would be difficult to assess whether any of the six conditions were favorable or unfavorable to productivity unless some standard of comparison were introduced. Such a condition is most appropriately given by the case in which the problem task is to be solved by individuals rather than crews. For this reason, a seventh condition was introduced, a baseline condition in which individuals operated alone.

Task Considerations

As was spelled out previously, many of the required activities of a C^3-crew can be interpreted in a problem solving context, specifically as a task comparable to template matching (Lindsay and Norman, 1972). The analogy of template matching was thought to have sufficient merit to be taken quite literally. For this reason, crews (or, in the baseline condition, individuals) were given a task involving repeated application of a template to a problem situation until a solution was achieved. In the actual field work of a C^3-crew, the set of required activities regularly involves application of substantial perceptual and conceptual skills, typically of abstract and spatial reasoning. Since skills of this order are considered to be closely linked to general intelligence (Wechsler, 1958) and are therefore thought to be fairly stable over time, they are not easily transferable from one team member to another through observation learning or instruction, or by other means of producing a behavioral change. In performing such a task, pronounced individual differences can be found, and these differences are stable over time. A task with such characteristics was therefore developed for the present study.

Dependent Variables

Conceptually there is only one dependent variable to be dealt with, and it is one that has been at or near the focus of discussion all along, namely productivity. When it comes to operationalizing this variable, the matter becomes more complex, for indeed productivity can be defined in a number of alternate ways. Commonly the preferred ways of defining it involve an assessment of time to solution, of accuracy, or of both. For the purposes of this study it was decided that time and accuracy were of equal importance, and the instructions to the subjects made this principle explicit. This decision dictated that both variables be given equal weight in a transformed measure of productivity. Of course, it was also required that such a transformation would be distributed in a manner that reasonably approaches a normal distribution. Finally, it was considered desirable that such a transformation have an element of elegance and concomitant face validity, specifically that it would not be blemished by contrived constants. As will be seen, these requirements were met by using a transformed dependent variable which was the sum of the logarithms of time and errors.

SECTION 3

METHOD

In accordance with considerations developed previously, the study employed the procedure of considering the performance of a dyad (a two-person crew) as the dependent variable of interest, comparing it to the baseline performance of individual subjects.

EXPERIMENTAL DESIGN

The research plan required a mixed three-factor design with 3 x 2 x 3 cells. Function allocation, a between-groups factor, had three levels, and degree of communication, also a between-groups factor, had two levels, as discussed above. A third factor, practice (within-groups), was presented in three levels to correspond to three sessions over which the study was conducted. Each of the six groups consisted of four dyads. After the three sessions in which the dyads worked together, each individual dyad member was given one additional session alone. The resulting data were to be used as covariates to control for the effect of individual differences on crew performance. In addition to these six cells of four dyads each, eight individual subjects in a baseline condition were tested individually. Just as each of the subjects in the dyadic conditions had a total of four sessions, so did the subjects in the baseline condition. In nearly all cases the four sessions took place on consecutive days, except that the fourth session was separated from the third one by a weekend in several instances. The effects of this irregularity were considered negligible.

SUBJECTS

Subjects were Air Force military and civilian volunteers and paid volunteers recruited from a large state university. The subjects were between 18 and 30 years of age. Assignment to conditions was based on the order in which subjects signed up for the study and on scheduling considerations. Care was taken that dyad members had at most a passing acquaintance with each other before the study.

EQUIPMENT

A PDP 11/34 computer with VS11 graphics system was used for experimental control and data collection. Responses crucial to the problem solving task were manual depressions of push buttons on two identical push button response boxes, one for each dyad member. All push button responses were recorded in real time. Two color monitors, containing identical displays at all times, presented the problem task to the subjects. In those conditions in which subjects had full communication, they were located side by side in an enclosed experimental room. When communication was restricted, the subjects were isolated from each other and could not see each other. They could still have talked with each other with raised voice, but were instructed not to do so, and indeed they did not. Throughout all sessions subjects were observed (with their knowledge and consent) on video and audio monitoring equipment.

THE TASK

Each session lasted 45 minutes plus the amount of time required by the dyad or the subject to finish the problem solving trial in progress. On each trial, both dyad members saw identical displays on their separate monitors consisting of two horizontal bar graphs, each containing six pairs of bars (see Figure 1). The wide, asymmetrical graph on the left is the "problem field", the narrow, symmetrical one on the right is a pair of "templates". The task requires subjects to modify the problem field successively until all six pairs of bars are of equal length, so that their borders form a straight, vertical line in the center of the problem field. Modification takes place by adding either the left or the right template to the problem field. When a template is added, all six bars are added simultaneously, changing the length of all bars in the problem field. Before adding one template or the other, the templates may be scrolled up or down. When they are scrolled, each template pair moves up or down one position, with the top pair moving to the bottom or the bottom pair to the top. It is necessary to scroll the templates to several positions to solve the problem. For an efficient solution the left template must be added in some positions, the right one in others. (A sub-optimal solution, requiring a greater number of steps, is possible even when only the left or only the right template is added.) Each problem is generated randomly with proper restrictions so that a solution can be achieved in ten addition steps. The

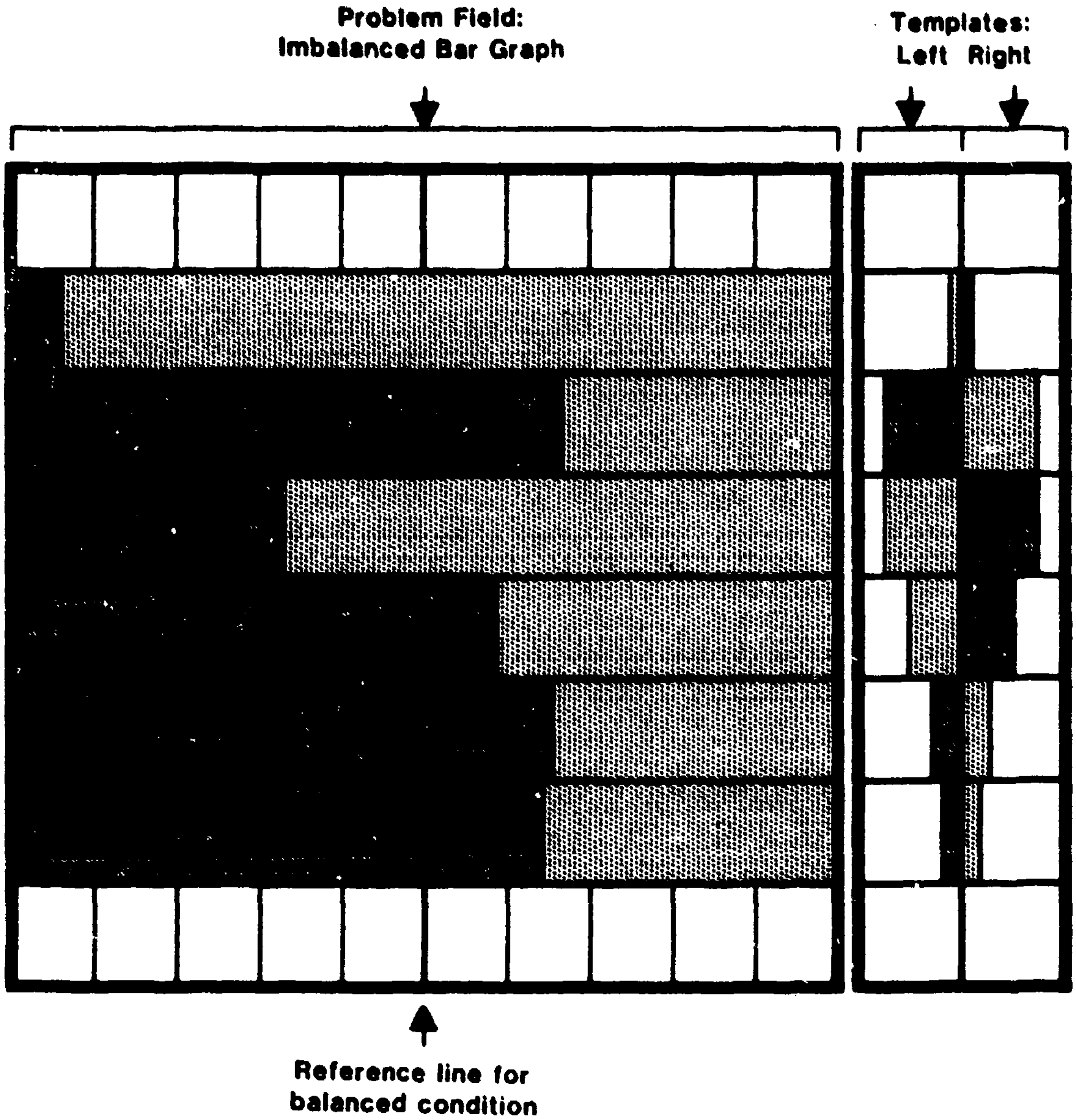

FIGURE 1. Problem Solving Task Display

order of these steps is irrelevant. Incorrect additions can be corrected by adding the opposite template, but as soon as such an error has been made, a solution requires more than the minimum number of steps. Thus twelve steps are required for the solution when one error has been made, 14 steps with two errors, and so forth. No matter how many errors are made in an attempt to solve the task, the problem cannot be rendered unsolvable, for even when the border between a pair of bars in the problem field exceeds the display boundary, the computer algorithm still retains the position it would have if the display was much larger.

PROCEDURE

The subjects used response panels, one per dyad member, to manipulate features of the display. These panels had six microswitch pushbuttons. Four of the buttons were arranged to be located at the points of a cross. The top and bottom buttons were used to scroll the templates up or down, the right and left buttons to add the right template or the left one. The two remaining buttons did not change aspects of the problem, but were used to transfer control. Even though both members of a dyad could control events on the screen, one of them only had control of them at any given time. The subject who did not have control could not scroll or add templates. However, control could be transferred between dyad members at any time and by either member. The two remaining buttons, then, were used to transfer control. One was used to take control from the other person, while the other was used to render control to the other person. Thus either subject was able to transfer control to or from the other subject, even if the other person was unhappy with this transfer. In fact, the possibility of extensive, unproductive control transfers was built into the experimental arrangement. Control status was displayed on both screens at all times. Thus subjects were always able to check who had control. Each control transfer was also accompanied by a brief acoustical signal.

Subjects in all treatment conditions were apprised of the nature of the task (with appropriate modifications for the baseline condition employing single subjects). Where full communication between dyad members was part of the experimental treatment, subjects were instructed that they should feel free to discuss any aspects of the task at any time. Subjects working under restricted communication conditions were instructed not even to discuss the task with their partners between sessions. It was pointed out to them that even though they could not talk to each other, they still could share their wishes or ideas with each other by means of their actions as they would be reflected on the screen.

The situation described thus far details the task as it was encountered by subjects in conditions in which there was no restriction in functions, where there was full overlap of functions and where each dyad member was able to carry out all aspects of the task. In the condition of intermediate function restriction, the task was changed such that one subject could only scroll up and add the right template, while the other subject could only scroll down and add the left template. As was stipulated before, this condition still permitted each subject to solve the problem alone, but not in an optimal fashion. If a subject wished to scroll up the templates by one position, but was restricted to scrolling down, the subject could achieve the desired template position either by transfering control to the other subject and thus having the partner perform the appropriate step, or by retaining control and scrolling down by five positions. Similarly, the problem could be solved by adding only one template. This solution, however, required many more steps than the ten associated with an optimal solution.

A third level of function allocation required that function overlap between crew members was completely removed from the task structure. In the present context, this requirement was met by restricting one dyad member to the function of scrolling the templates up and down, while the other subject could only add either template. Under these circumstances it was impossible to solve the problem alone.

Subjects in the single-subject baseline condition had access to all four functions of scrolling up and down the templates and of adding either one of them as they chose. For them the control transfer buttons served no purpose.

To meet the goal of achieving a subjectively equal weighting of speed and accuracy in performance, subjects were instructed explicitly that they should try to solve each problem as efficiently as possible, and that this meant they should work as quickly as possible and try to solve the problem in as few template additions as possible. To give subjects information on their performance, a counter in the monitor displays advised them how many addition steps they had made on the current problem. Scrolling steps were not counted for the subjects, and no consideration was given to them in subsequent analysis.

SECTION 4

RESULTS

The results obtained in this study are presented in three sections. First an analysis is made to ascertain the merits of the major dependent variables. Major results addressing the hypothetical formulations of the study are presented next. Finally, incidental results are offered for further theory development.

PRELIMINARY ANALYSIS

As was suggested previously, it was desirable to deal with a single dependent variable that incorporated all essential features of crew productivity. Two variables were the most likely candidates for consideration, namely time required for solution, and number of steps employed for the achievement of the solution. Initial analysis of these variables showed that they both were distributed with excessive positive skew, as was to be expected. This skew was sufficient to render a direct parametric analysis of these "raw" data highly suspect. By transforming these data to obtain their natural logarithms (ln), several interesting outcomes occurred. First, the resulting data sets, both for solution time and for solution steps, closely approximated normal distributions, showing very little skew or kurtosis. Second, the correlation between ln(solution time) and ln(solution steps), based on the performance of all 48 dyadic subjects during their fourth session, was $r=.062$. This value was interpreted to suggest that the two variables were reasonably independent of each other, that subjects showed no major tendency to trade off one against the other, and that the variables could be added without creating a meaningless hybrid. Third, the within-dyad error variances of the two distributions were quite similar, with $MS(\ln(time))=.76$ and $MS(\ln(steps))=.69$. Both variables would thus be weighted nearly equally in a composite variable consisting of the sum of ln(time) and ln(steps).

A composite dependent variable, ln(time)+ln(steps), was also calculated and scrutinized for its characteristics. It had a nearly normal distribution with virtually no skew, although it was slightly leptokurtic.

Based on these preliminary results, all inferential analyses were performed, as a matter of course, on the three transformations discussed, namely ln(time), ln(steps), and ln(time)+ln(steps). For the sake of efficient presentation, these variables are identified in the balance of the report as ln(t), ln(s), and ln(ts). While all three variables were analyzed and reported, it was felt that the most important index of the three in terms of applied utility would be the last one.

PRIMARY RESULTS

Primary results of the study were those that addressed specifically the hypothetical formulations which were to be tested regarding the effects of the independent variables.

Session Effects

The data were collected over three sessions (not counting the last control session) since it was expected that the effects of training might not be the same in all treatment conditions. This expectation was not confirmed. Training had the commonly found major effect, shown as a linear decrease in ln(t), ln(s), and ln(ts) with $F=83.47$, 23.83, and 64.88, respectively ($df=1,18$, $p<.05$ in all cases). These linear trends were the only significant sources of variation associated with sessions, as main effects or in interaction with any other variable. Consequently all remaining major results are related to between-dyad phenomena.

Treatment Comparisons

Since there were no interactions between sessions and other variables, the following results refer to the means of the three sessions (although they were not calculated that way). Table 1 presents the mean performance per condition for each of the six major treatment conditions, as well as for the single-subject control condition ($n=8$), and it does so for each of the dependent measures, ln(t), ln(s), and ln(ts). Significant overall F-ratios between the seven conditions were associated with ln(s) and ln(ts) ($F=2.58$ and

TABLE 1. Mean Performance in Sessions 1 to 3 by Dyads Under Three Conditions of Function Overlap and Two Conditions of Communication, and by Single-Subject Controls.

Response Measure	Communication	Function Overlap			Control
		Full	Partial	None	
$\ln(t)_1$	Full	5.87	6.01	5.50	5.50
	Restricted	5.67	5.84	5.63	
$\ln(s)_2$	Full	1.27	1.16	0.29	1.14
	Restricted	1.67	2.41	1.39	
$\ln(ts)_3$	Full	7.14	7.17	5.79	6.64
	Restricted	7.34	8.25	7.02	

Footnotes:
1: ln(t) = natural logarithm of solution time in seconds
2: ln(s) = natural logarithm of number of solution steps
3: ln(ts) = sum of ln(t) and ln(s)

2.78, respectively, $df=6,25$, $p<.05$), but not with ln(t) ($F>1$). In fact, no significant effects at all were associated with ln(t) except for the sessions effect already mentioned. The significant overall results associated with ln(s) and ln(ts) were followed up with orthogonal contrasts. These analyses indicated for both data sets that the mean performance for the condition of separate functions and full communication was significantly lower (i.e., better) than for all other conditions, while the mean performance for the condition of partial function overlap and restricted communication was significantly higher (i.e., poorer) than for the remaining conditions, including the control condition ($F=14.10$ and 14.62, respectively, $df=1,25$, $p<.05$). Virtually identical results were obtained when the control condition was eliminated from the analysis. The control condition did not produce results different from dyadic mean performance.

Factorial Analyses

The same data were also analyzed in terms of the underlying experimental design, namely as factorial experiments. The single-subject control condition was excluded from these analyses. For ln(s) a significant main effect associated with communication was found ($F=7.48$, $df=1,18$, $p<.05$). The main effect for function allocation was not significant, and neither was the interaction. A significant main effect associated with communication was also found for ln(ts) ($F=4.54$, $df=1,18$, $p<.05$). For this combined variable, the effect of function allocation was also significant ($F=3.79$, $df=2,18$, $p<.05$). Again, the interaction was not significant.

Covariance Analyses

As problem solving skills may be expected to be stable over time because they are presumably linked to intellectual features, much of the between-dyad error variance may be due to pre-experimental subject variables. To eliminate some of this noise variation, analyses of covariance were performed to parallel those analyses already described. The covariates used in these analyses of covariance were performance during the fourth session, by either the better or the poorer dyad member, or the mean of the two measures. This procedure did indeed eliminate considerable between-dyad error variance. The fourth-session performance of the better dyad member accounted for 58% of the error variance, the performance of the poorer dyad member for 49%, and the mean performance of the two for 72%. But the reduction in error variation was accompanied across the board by comparable reductions in treatment variation. Consequently, no systematic changes from the findings based on the analyses of variance occurred in the analyses of covariance.

SECONDARY RESULTS

It was of incidental interest to scrutinize performance of individuals in the fourth session after they had worked as team members for three sessions. The linear improvement observed over the first three sessions was not repeated from the third to the fourth session. Mean solution time ($\ln(t)$) did decrease significantly from the third to the fourth session ($F=5.28$, $df=1,18$, $p<.05$), but this effect was offset by an increase in the number of steps required for solution as reflected in $\ln(s)$ ($F=5.08$, $df=1,18$, $p<.05$). In overall performance ($\ln(ts)$) there was virtually no change from the third session to the fourth.

Inspection of the transformed scores suggested that there were substantial differences in fourth session performance between better and poorer dyad members, certainly more than would have appeared attributable to chance. The differences seemed to prevail for all three measures, $\ln(t)$, $\ln(s)$, and $\ln(ts)$. However, the observation seemed virtually immune to an inferential statistical test, since the values of the dependent variable were assigned to the "better" or "poorer" category on the basis of their relative magnitude. Another manner in which these within-dyad differences can be conceptualized is to think of them as the residual left from the total sum of squares after removing the sum of squares associated with between-dyad differences. This partitioning procedure permitted the calculation of the proper F-ratios (except that the variance in the denominator was inflated by treatment effects, thus yielding conservative F-ratios). The F-ratios were significant in all three cases ($F=3.86$, 2.30, and 7.04 for $\ln(t)$, $\ln(s)$, and $\ln(ts)$, respectively, with $df=23,23$ for each analysis, $p<.05$).

SECTION 5

DISCUSSION

Despite the complexity of the field a few major findings of the current study were quite straightforward. Perhaps the clearest one was the result that improvement over sessions did not seem to interact with any other variable. One implication of this result is that whatever treatment effects may be in effect, they do not seem to affect learning rate for the task in major differential ways. Rather, they act more nearly like additive constants to the learning curve. An important inference that may be drawn from this finding for application in the field is this: Experience in a particular C^3-crew condition may certainly improve problem solving performance, but it will not undo beneficial or detrimental effects of work conditions like communication and function allocation.

A second unambiguous result is that crew performance, on the average, was not different from the performance of subjects in the single-subject control condition. This result is, of course, consistent with evidence that has been provided in the literature (e.g. Hill, 1982) and that has been discussed previously. At the same time, it continues to be disconcerting.

When teams solve complex problems, communication has a general positive effect on productivity. This positive effect is specific to the number of steps taken (or number of errors made): Communicating crews make fewer errors, on the average, than crews whose members are isolated from each other. The amount of time required for problem solution is not affected by communication, but total crew productivity is higher for communicating crews.

A possible reason for this differential effect is that the opportunity to communicate may have both positive and negative effects which cancel each other when solution time is the measure used. Communication may help the crew find a faster solution, but it may also interfere by allowing unproductive exchanges to occur. Subject monitoring revealed considerable time periods of banter and chitchat in conditions of full communication.

Even though there is no question that communication has an overall positive effect on problem solving productivity, one is hard pressed when attempting to understand this effect at the different levels of function overlap. In particular, the beneficial effect of communication is notably absent when crew members have full function overlap (see Table 1), i.e., when it would appear that it is most important for the crew to be in agreement regarding who does what. Any effort to capture the relevant features of these results in terms of a factorial interpretation encounters obvious limitations.

The main effect of degree of function overlap is even more elusive than that of communication. Function overlap showed an effect only in the analysis of ln(ts), the combined index of productivity developed for this task. Any further attempt to narrow down the effect of this variable in a factorial manner would be unconvincing, primarily because the factors do not seem to have a meaningful existence separately from each other. Rather, the factor combinations form six unique treatment conditions. An analysis of relative performance in the individual treatment cells was therefore considered far more revealing than factorial analysis.

An analysis of treatment comparisons showed that the single condition resulting in superior performance (both in total productivity and in number of required solution steps) was the one in which crew members could communicate fully with each other, and their functions did not overlap. To workers in the field this result may not be surprising since it is consistent with various operational crew arrangements. On the other hand, an arrangement that is even more common is one involving partial or even full overlap of functions. In operational settings the rationale likely to be used is that some function overlap is advantageous since it incorporates the safety feature of redundancy. This argument may be valid for various tasks, particularly those involving less central processes such as detection or recognition. In a problem solving task like the one used in this study, where feature analysis and synthesis as well as attributive judgment is involved, there seems to be little benefit to be gained from a safety feature. Evidently those purposes that are served by some function overlap are not relevant in a problem solving task, or they may be replaced by the option of communication. By contrast, the effect of role confusion and unclear operating procedures associated with function overlap may be quite debilitating when abstract reasoning is required.

This conceptual interpretation is further supported by the performance of crews under conditions of partial overlap of function, coupled with restricted communication. Under these circumstances teams performed significantly more poorly than under any other conditions, both in terms of the index of productivity and in terms of errors made, or steps taken to solve the problem. Here the biggest problem encountered by the crew seemed to be to determine just who should be doing what at any given time. In fact, on some occasions subjects alternated between each other from one problem to the next, so that one subject alone was solving the entire problem, forcing a most inefficient strategy. It seemed that in this manner, at least, they did not have to worry about coordinating their efforts.

The implication seems rather clear: C^3-crews which are required to solve conceptual problems are likely to operate most productively if they have clearly defined, separate functions, and if they can discuss task aspects freely with each other. They are likely to operate least productively if their functions overlap partially, and are consequently not clearly delineated, and if communication is restricted.

To generalize these results is a matter that requires some caution. The representativeness of the task used in this experiment may be the crucial issue. The obtained results are likely to be valid only for C^3-conditions involving a substantial amount of conceptual processing. The question whether other task characteristics would yield different results cannot be answered on the basis of present findings. The major benefit of the task that was used here is that it seems to represent somewhat of the "think tank" challenges encountered in many current C^3-situations.

In terms of statistical theory, non-significant results are no results at all. When they occur in large number, however, they represent a state of affairs that could profit from a comment. Such is the case when it comes to reviewing the outcomes of the multiple analyses of covariance conducted in conjunction with this study, all of them overwhelmingly refusing to yield significant results where the corresponding analyses of variance had not done so, either. Such "failure" to reap significant results seems open to one interpretation only. The analyses of covariance eliminated variability both from error and from treatment. This result can be considered a matter of eliminating the contribution of the covariate. This covariate, however, was performance of the individual subjects (as contrasted with dyads). To put it another way, elimination of individual differences between subjects has no demonstrable effect on crew performance. This conclusion is speculative, of course, but it suggests that there may be room for further studies that focus on issues relating to qualitative differences between individuals and groups. The present implication, at least, is that groups are decidedly different behavioral units from the sums of their individual members. An extrapolation of this statement would be that it becomes important for persons in charge of crew development to look at crew behavior, rather than the behavior of individual crew members (as is common practice), as a predictor of future crew productivity.

The distinction between individual and crew performance is also encouraged by the results regarding differences between dyad members when they had to operate alone during their last session. These marked productivity differences in terms of solution time, solution steps, and the composite index of productivity, suggest that the crew experience, even over just three sessions, accentuated whatever differences there might have been between dyad members in the first place. At the end of the third dyadic session, dyads typically had one member who was notably better than the other at performing the task, with a greater difference prevailing between them than would be expected statistically. This differentiation had not been built into the experimental design of the study but emerged spontaneously from the group experience, regardless of treatment condition. It is not consistent with the view that team members tend to emulate each other or take on response styles from each other which then make up the overall team response style. Rather, the weight of the evidence suggests that teams act in a manner qualitatively different from each member.

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SECTION 6

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